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FINAL REPORT

CONTRACT NAS 9-5880

"DEVELOPMENT OF INSTRUMENTATION FOR MEASUREMENT OF BONE DENSITY"

June 6, 1967

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"DEVELOPMENT OF INSTRUMENTATION FOR MEASUREMENT OF BONE DENSITY"

PART I: Bone Density Instrumentation

A. Introduction

For several decades methods have been sought for determining the density of bones in the living human skeleton. Mack, et al., have developed and described techniques and equipment used for the quantitative roentgenographic measurement of bone density.[1,2,3,4] The roentgenographic technique consists of relating the optical transmittance of a roentgenogram of a bone to the mineral density of the bone.

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[1] Mack, P. B., A. T. O'Brien, J. M. Smith, and A. W. Bauman, "Method for Estimating Degree of Mineralization of Bones From Tracings of Roentgenograms," Science 89, p. 467, (1939).

[2] Mack, P. B., W. N. Brown, Jr., and H. D. Trapp, "The Quantitative Evaluation of Bone Density," American Journal of Roentgenology 66, p. 808, (1949).

[3] Mack, P. B., G. P. Vose, and J. D. Nelson, "New Equipment Development in the Roentgenological Measurement of Bone Density," American Journal of Roentgenology 82, p. 303, (1959).

[4] Anderson, J. B., J. Shimmins, and D. A. Smith, "A New Technique for the Measurement of Metacarpal Density", British Journal of Radiography 39, p. 443, (1966).

The first procedures used to determine bone density from roentgenograms consisted of manual manipulation of the optical transmittance data. As roentgenographic procedures evolved, instrumentation techniques were applied to various phases of the data processing. This contract provided for a program to optimize the Texas Woman's University (TWU) roentgenographic technique. This program was effected in two phases. Phase I included the selection and integration of a digital computer into the TWU installation, and Phase II included an evaluation of the digital system as well as a study of various alternative instrumentation systems.

B. TWU Analog Bone Density Computer System

The purpose of the bone density measuring system is to evaluate the integrated bone density over a specific cross-section of bone. The problem may be described as follows.

A roentgenogram of a standard aluminum calibration wedge and the desired bone is obtained in a single exposure. This insures uniform exposure and processing conditions for the reference and the variable to be measured. The developed film is then scanned to measure optical transmittance by means of a scanning microdensitometer. First, the image of the wedge is scanned to determine the relation between optical transmittance and the thickness of the reference wedge as recorded on the particular film. (The calibration wedge is a wedge-shaped object whose thickness varies linearly with distance along the wedge and is made out of a material of known x-ray absorption/scattering properties.) The graphical representation of the optical scanner output for a scan of the wedge image may look similar to the curve shown in Figure 1.

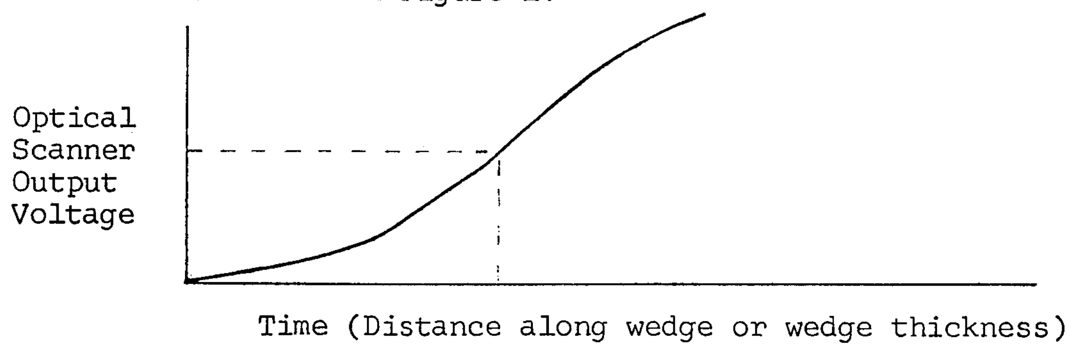


FIGURE 1. Typical Wedge Scan Curve

Secondly, the bone image is scanned along the desired cross-section. A typical curve is depicted in Figure 2.

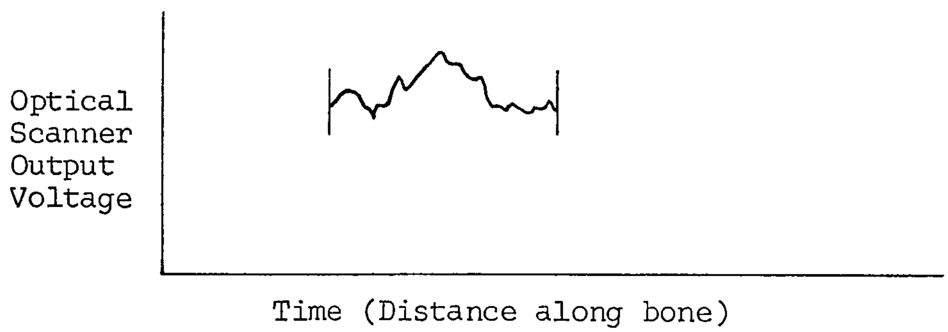


FIGURE 2. Typical Bone Scan Curve

The curves shown in Figures 1 and 2 represent the basic inputs for measurement of bone density. The computation system must then convert the optical scanner voltage output for the bone scan to a curve of equivalent density (in terms of wedge thickness) and integrate the area under the resulting curve. The conversion between optical scanner output for the bone scan and equivalent wedge thickness is made using the first curve. The curve is entered at the value of optical scanner output and the wedge thickness is read on the abscissa. This equivalent wedge thickness is used in the subsequent integration of the density.

In the analog system in use at Texas Woman's University, the conversion between optical scanner output during the bone scan and equivalent wedge thickness is made by using a nonlinear resistance slidewire output from a chart recorder. The nonlinearity can be manually adjusted so that the output is approximately linear during a wedge scan. The integration is accomplished by using an electro-mechanical integrator. A block diagram of this system is shown in Figure 3.

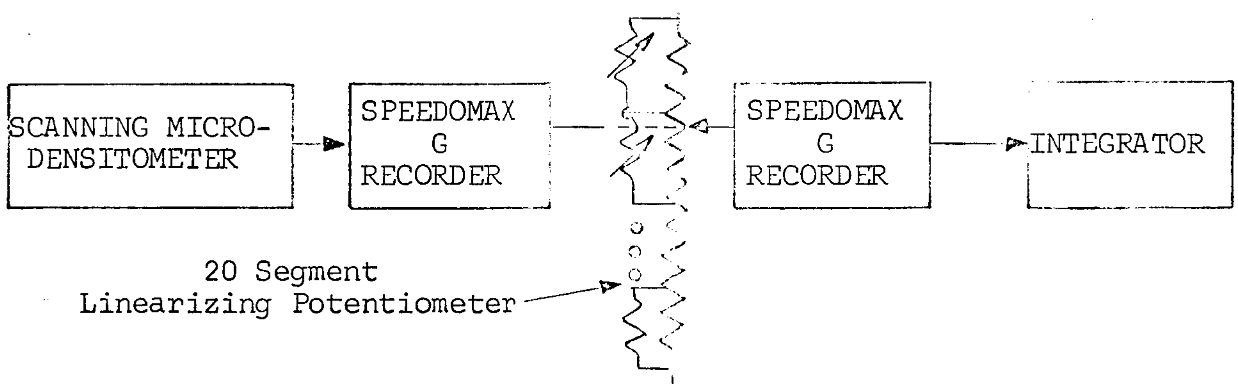


FIGURE 3. Block Diagram of Analog Bone Density Computer System

The scanning microdensitometer used in the TWU installation is a modified Knorr-Albers Microphotometer manufactured by Leeds and Northrup Company (catalog EM9-90(2)1953). The Knorr-Albers Microdensitometer consists of two units: (1) a scanning unit containing the film drive mechanism, optics, preamplifier and controls, (Dwg. No. D-2145), and (2) a Leeds and Northrup Speedomax "G" Recorder (Dwg. No. 555-672-A-10). The film to be scanned is clamped between two plates of glass mounted in a motor-driven mechanical assembly configured so as to move the film along a given path at a constant speed (selectable; 0.1, 0.2, 0.5, 1, 2, 5, 10, 20 or 50 mm per minute). A straight-line filament lamp is used as the light source. The image of the filament is focused upon the film through a ÷10 lens (this provides a rectangular illuminated area on the film of approximately 0.01mm x 1.5mm). The light transmitted through the film is then focused through a x10 lens upon a ground glass surface. The photocell is responsive to the light upon the ground glass surface. A sketch of the scanning unit is shown in Figure A.

The voltage from the preamplifier (functional with the transmitted light) is sensed and recorded by the Speedomax "G" Recorder. This recorder is of the self-balancing servo type having a full scale deflection sensitivity of approximately 7mv. The 20-segment linearizing potentiometer is driven by the servomotor. A sketch of the recorder is shown in Figure 5A. The operator sequentially adjusts the trimming potentiometers P1 through P20 to compensate for the non-linear characteristics of the curve. Each potentiometer adjusts the slope of the resultant curve over 1/20 of the range. A template placed

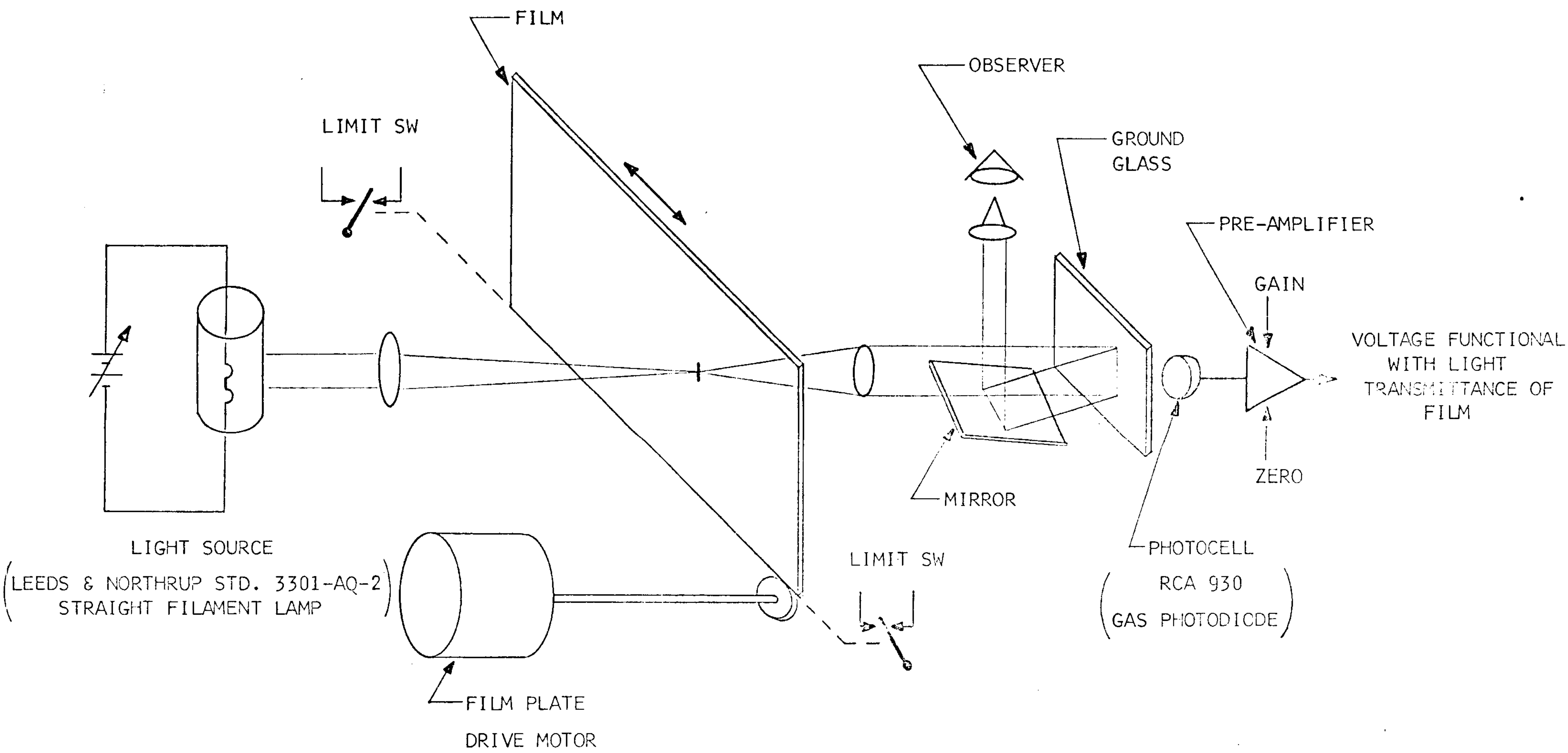
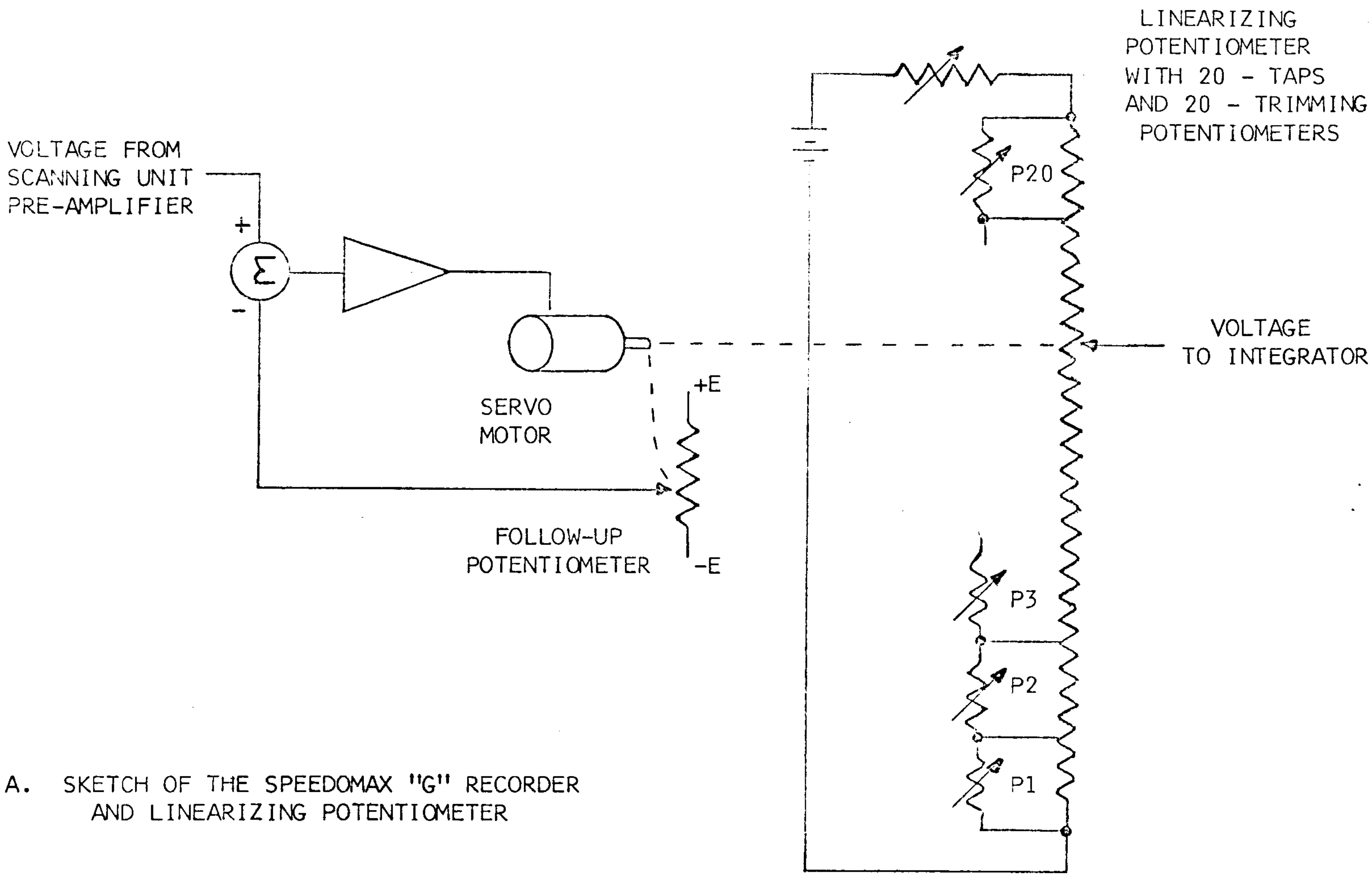
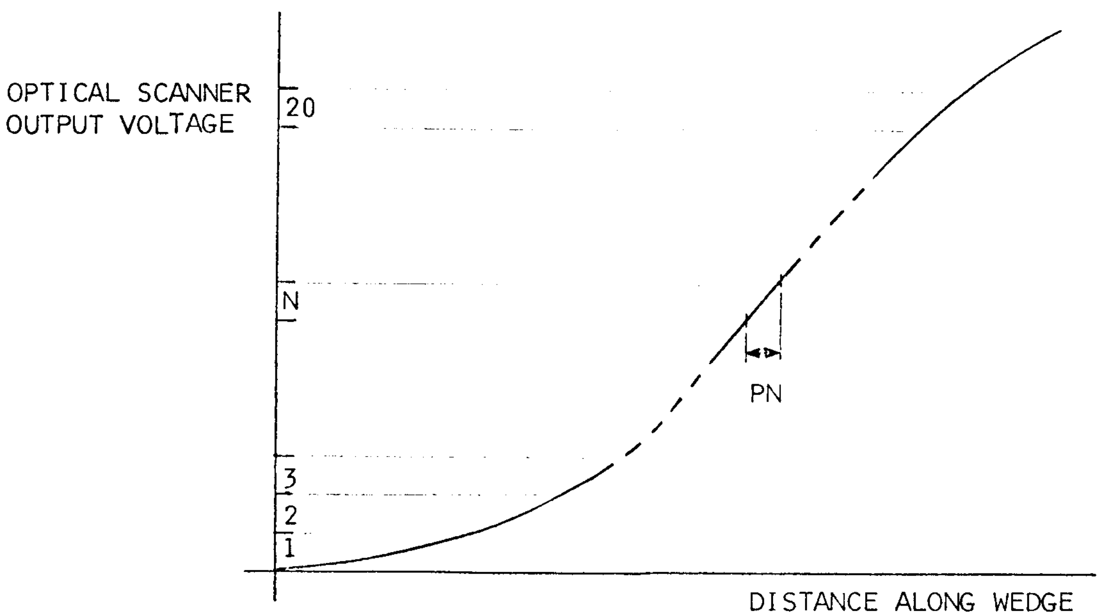


FIGURE 4. SKETCH OF KNORR-ALBERS SCANNING UNIT



A. SKETCH OF THE SPEEDOMAX "G" RECORDER AND LINEARIZING POTENTIOMETER



B. WEDGE TRACING LINEARIZATION

FIGURE 5. SKETCH OF CURVE LINEARIZATION MECHANISM

over the segment of the curve to be corrected provides the operator with a direct readout of the proper adjustment of that potentiometer (the details of this process are given in a paper by Mack)[5].

A second Speedomax "G" recorder provides a record of the linearized data, and an electro-mechanical integrator (Instrom Integrator) provides the capability of measuring the area under the curve.

C. General Requirements of Bone Density Instrumentation Systems

This section will outline some of the general requirements of various aspects of the subject technique. Mack employs a linear wedge as the calibration object. It is not necessary that the calibration object have a linear thickness function. In general, the calibration object must have a continuous and monotonic thickness function over the desired thickness range. However, the choice of a linear thickness function provides some desirable characteristics that permit overall system simplification.

The response functions of all system elements up to the linearizing potentiometer must be continuous and monotonic, i.e., the input/output and output/input relations must be unique. Note that linear responses of these elements is not required. Functions performed after the linearizing process must be linear (i.e., the second Speedomax "G" recorder and the integrator).

[5]Mack, P. B., G. P. Vose, and J. D. Nelson, "New Equipment Development in the Roentgenological Measurement of Bone Density," American Journal of Roentgenology 82, p. 303, (1959).

D. Alternative Instrumentation Systems

Ths analog system in use at TWU reflects state-of-the-art instrumentation for its time of construction (1940's). The inherent accuracy of this system is entirely adequate; however, as more and more data is processed, there is interest in speeding up the data reduction process. Several instrumentation systems have been suggested and analyzed that provide increased degrees of automation and speed to the process (automation of operator-performed functions also tend to increase the overall system accuracy and reliability). Four such systems will be discussed in the following paragraphs.

1. Additional automation of present analog system.

The principle drawback to the present system is the requirement of an operator to perform the step-by-step linearization process for each film (i.e., the sequential adjustment of 20 potentiometers). Several methods of automatically adjusting the 20 potentiometers can be implemented. Such schemes would employ either an independent servomechanism to set each potentiometer (20 servo systems) or a clutching arrangement so that one servo could be used to set all 20 potentiometers. The film drive plate could be stepped in increments that divide the output voltage into 20 equal steps - at each step the potentiometer-setting servo would set the corresponding trimming potentiometer so that the output has the proper slope.

Implementation of this type system would be very expensive and would result in a very bulky system. The switching and control of such a system would be relatively complicated.

2. Comparison system.

For a linear wedge-shaped calibrating object, the density is a linear function of distance along the wedge. Thus, if a nulling type servomechanism is used to position a densitometer along the calibrating roentgenogram so that it is always at a point that has the same optical transmittance as the bone roentgenogram, then the position of this densitometer can be interpreted as a measure of bone density. In the foregoing method, the calibration data from the wedge roentgenogram is transferred to a linearizing potentiometer and subsequently used to process data. In this method the calibrating data stored on the film is used directly by means of a second densitometer. A comparison type system is shown in Figure 6.

The bone roentgenogram is separated from the wedge roentgenogram and each is placed in its appropriate holder. A light source simultaneously focuses light through both roentgenograms. Photocells detect the light transmitted through each film. A summation circuit compares the photocell outputs and provides an error signal to a servomotor that moves the wedge film in the direction to equalize the photocell outputs. Hence, as the bone film is scanned at a constant

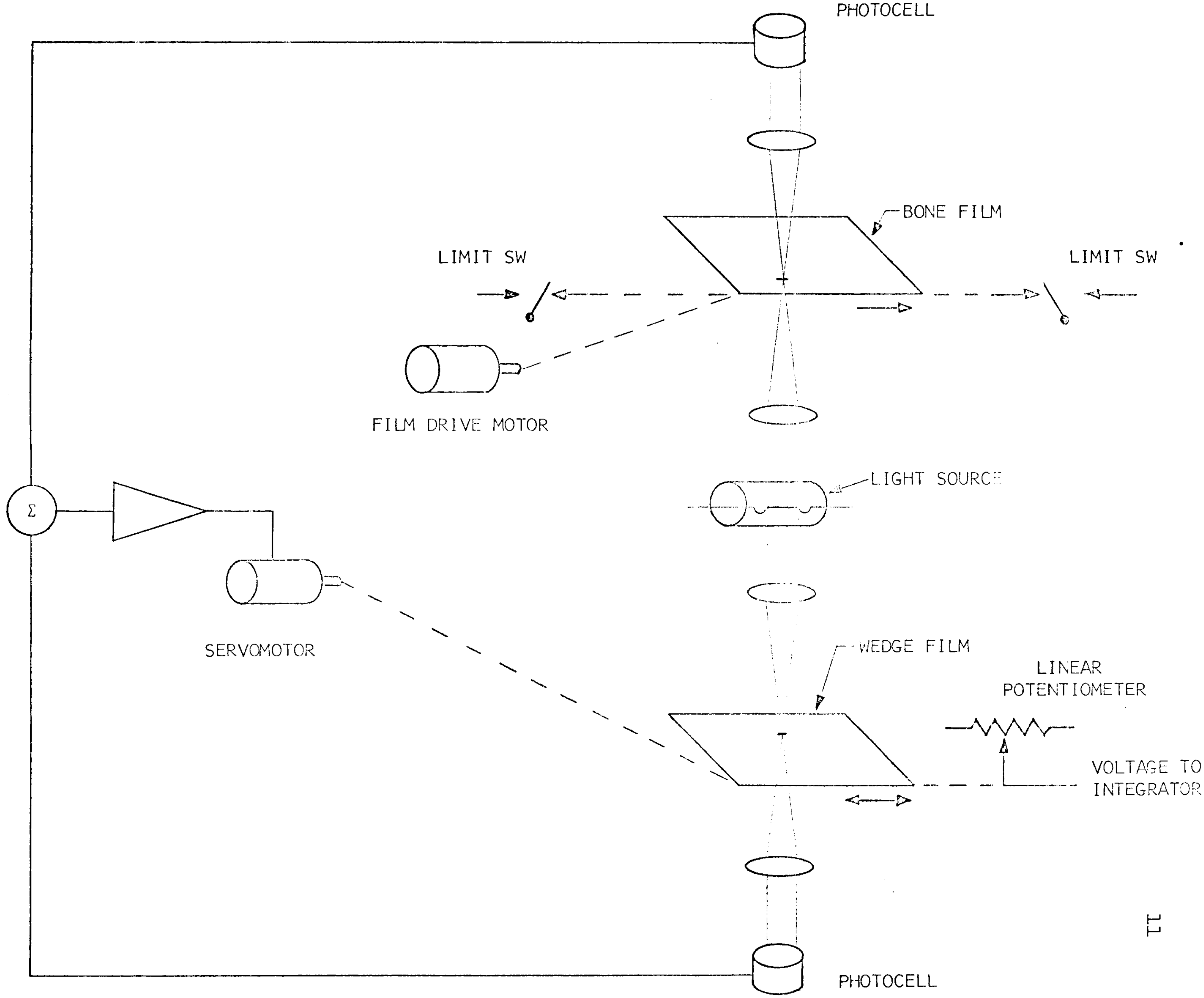


FIGURE 6. SKETCH OF COMPARISON SYSTEM

rate as determined by the film drive motor, the servomotor and associated circuitry tends to keep the wedge film positioned at a point of equal optical transmittance. A linear potentiometer sensing the position of the wedge film provides a voltage proportional to distance along the wedge. This is the voltage to be integrated by the integrator.

The advantages of this system are simplicity and accuracy. The arrangement sketched in Figure 7 utilizes one light source to scan both films, thereby eliminating the need to balance or keep constant the light sources. Although linear response of the photocells is not required, the response characteristics must be very nearly alike. This requirement could be eliminated by a mirror and light chopper arrangement so that one photocell alternately senses the light beam through the bone film and the light beam through the wedge film. The inherent accuracy is better than the present system. The primary disadvantage of this system is that two film holder and drive mechanisms are required. Ultimately this system could be constructed as a small table-top unit.

3. General purpose digital computer system.

Phase I of this contract consisted of incorporating a general-purpose digital computer into the TWU system. A Digital Equipment Corporation PDP-8 computer was used for this purpose. The details concerning the installation and use of this computer are outlined in the Phase I Report.[6] As the wedge roentgenogram is scanned, the optical transmittance data is sampled and stored in the computer's memory. The computer is programmed to perform the desired manipulations of this data.

This system affords almost any desired degree of accuracy at the expense of computer memory space. This is a relatively expensive and bulky approach to the instrumentation problem.

4. Special purpose digital computer.

The non-linear processes encountered in the roentgenographic techniques are the results of well known physical processes. It is quite possible that the optical transmittance function for the wedge roentgenogram could be expressed as a rather simple equation with constants that could be determined with few (possibly one) sample points from the film. This would permit the storing of the wedge data in equation form in one of the small desk-calculator type digital computers that are now available. The data would then be processed in a semi-analytical manner for which these computers are ideally suited.

The details of this technique have not been pursued. It appears feasible and is listed here only as a possibility.

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[6] "Development of Instrumentation for Measurement of Bone Density", Phase I Report, Contract NAS 9-5880, January 10, 1967.

PART II: Evaluation of Digital System

A. Accuracy Analysis of Digital Bone Density Measuring Systems

The accuracy of the digital instrumentation for the measurement of bone density has been evaluated from data submitted by Texas Woman's University. The data has been evaluated on both a comparative basis (simultaneous bone scans) and absolute basis (simultaneous wedge scans). The analysis of the data indicates that the systems can be expected to agree to within approximately two percent.

During ten simulated bone density scans, the reference wedge image was rescanned instead of scanning a bone image. The data are shown in Table I. Theoretically, both the analog and digital system should indicate 6500 integrated counts during the rescan. The analog system indicated a sample mean of 6472 counts with a sample standard deviation of 31 counts. The digital system indicated a sample mean of 6491 with a sample standard deviation of 52 counts. Based on statistical tests at the 90% confidence level, the variability of the digital system cannot be shown to differ from the variability of the analog system. The tolerance intervals (at 90% confidence) expected to contain at least 95% of typical readings are 6380 to 6564 for the analog system and 6329 to 6653 for the digital system. Note that these readings appear abnormally wide compared to the standard deviation; this is because of the limited number of data points.

TABLE I

COMPARATIVE RESULTS OF ANALOG & DIGITAL BONE DENSITY MEASUREMENTS INCLUDING SCAN OF REFERENCE WEDGE

SUBJECT AND X-RAY DATE	TRACING DATE	INTEGRATED COUNTS UNDER WEDGE SCAN		INTEGRATED COUNTS UNDER BONE SCAN		PER CENT DIFFERENCE ON WEDGE	PER CENT DIFFERENCE ON BONE
		Analog	Digital	Analog	Digital		
V 9-8-66	2-27-67	6460	6510	11401	11397	0.80	-0.04
V 9-14-66	2-27-67	6461	6526	11039	11147	0.99	0.97
V 9-9-66	2-27-67	6449	6487	11719	11692	0.58	-0.23
V 7-28-66	2-27-67	6479	6522	11634	11604	0.66	-0.26
V 7-27-66	2-27-67	6482	6514	11218	11142	0.49	-0.68
V 7-26-66	2-27-67	6530	6498	11884	11777	-0.49	-0.90
V 7-24-66	2-28-67	6481	6452	11883	11789	-0.44	-0.79
V 7-22-66	2-28-67	6489	6539	11402	11359	0.76	-0.38
V 7-16-66	2-28-67	6479	6503	11247	11189	0.23	-0.52
V 7-18-66	2-28-67	6409	6358	11391	11335	-0.79	-0.49

The data submitted by Texas Woman's University contains both analog and digital bone density readings of 55 bone images evaluated prior to a final digital program correction (Table II) and 57 bone images evaluated after the program correction (Tables I and III). The program correction was a change in scale factor to be applied in the digital integration of the corrected wedge scan. The program correction was expected to increase the mean reading of the integrated bone scan by approximately 3% (depending on the number of sample points in the scan). There is no reason to suspect that the program correction would significantly affect the variance of the readings obtained on successive scans of the same bone.

In comparing the results of the analog and digital systems, the difference in readings was converted to a percentage of the analog reading. Because each density reading is actually a sum of many incremental readings, a gaussian or normal distribution of errors is expected and conventional tolerance interval estimates can be made.

The data obtained prior to the program change was checked to determine the form of its distribution. When plotted in a histogram, the data appeared gaussian and statistically the hypothesis that the data was gaussian could not be rejected even at the 25% confidence level. Based on the 55 data points before the program change, the sample mean error was 4.38% and the sample standard deviation was 1.95%.

TABLE II

COMPARATIVE RESULTS OF ANALOG AND DIGITAL BONE DENSITY MEASUREMENTS MADE PRIOR TO FINAL DIGITAL PROGRAM CHANGE

SUBJECT AND X-RAY DATE		TRACING DATE	INTEGRATED COUNTS UNDER BONE SCAN		PER CENT DIFFERENCE
			Analog	Digital	
2611	6-6-66	8-30-66	8151	8774	7.1
2611	6-6-66	8-31-66	8182	8773	6.7
2612	6-6-66	9-1-66	9097	9437	3.6
2612	6-6-66	9-2-66	9129	9421	3.1
2613	6-7-66	9-3-66	9769	10060	2.9
2613	6-7-66	9-5-66	9741	10335	5.7
2618	6-8-66	9-6-66	8682	8994	3.5
2618	6-8-66	9-7-66	9019	8703	-3.5
2619	6-8-66	9-8-66	5998	6459	7.1
2619	6-8-66	9-9-66	6045	6518	7.3
2620	6-9-66	9-10-66	8641	9100	5.0
2620	6-9-66	9-12-66	8697	9175	5.2
2621	6-9-66	9-13-66	8148	8600	5.3
2621	6-9-66	9-14-66	8139	8578	5.1
2624	6-10-66	9-15-66	8836	9030	2.1
2624	6-10-66	9-16-66	8849	9072	2.5
2625	6-10-66	9-17-66	8407	8778	4.2
2626	6-10-66	9-19-66	7712	8114	4.9
2623	6-10-66	9-20-66	9212	9461	2.6
2623	6-10-66	9-21-66	9184	9417	2.5
2628	6-11-66	9-22-66	9005	9351	3.7
2628	6-11-66	9-23-66	9082	9386	3.2
2630	6-13-66	9-24-66	6927	7480	7.4
2630	6-13-66	9-26-66	6987	7513	6.9
2631	6-13-66	9-27-66	8364	8746	4.4
2631	6-13-66	9-28-66	8410	8811	4.6
2632	6-14-66	9-29-66	8583	8904	3.6
2632	6-14-66	9-30-66	8640	8943	3.4
2633	6-14-66	10-1-66	8174	8506	3.9
2633	6-14-66	10-3-66	8251	8562	3.6

TABLE II (continued)

SUBJECT AND X-RAY DATE		TRACING DATE	INTEGRATED COUNTS UNDER BONE SCAN Analog	Digital	PER CENT DIFFERENCE
2615	6-7-66	10-4-66	8791	8951	1.8
2615	6-7-66	10-5-66	8906	9187	3.0
2634	6-14-66	10-6-66	8829	9251	4.6
2634	6-14-66	10-7-66	8892	9267	4.0
2635	6-14-66	10-8-66	7495	8016	6.5
2635	6-14-66	10-10-66	7481	7924	5.6
2636	6-15-66	10-11-66	7961	8419	5.4
2636	6-15-66	10-12-66	8001	8485	5.7
2637	6-15-66	10-13-66	7054	7476	5.6
2637	6-15-66	10-14-66	7096	7479	5.1
2638	6-16-66	10-15-66	6614	6999	5.5
2638	6-16-66	10-18-66	6548	6932	5.5
2639	6-17-66	10-19-66	8005	8380	4.5
2639	6-17-66	10-20-66	8029	8378	4.2
2641	6-20-66	10-21-66	5987	6364	6.0
2641	6-20-66	10-22-66	5948	6338	6.1
2642	6-20-66	10-24-66	8231	8665	5.0
2642	6-20-66	10-25-66	8219	8622	4.7
2643	6-20-66	10-26-66	6435	6869	6.3
2643	6-20-66	10-27-66	6481	6945	6.7
2644	6-21-66	10-28-66	7341	7624	4.3
2614	6-7-66	10-29-66	9464	9474	0.1
2640	6-17-66	10-31-66	8704	8896	2.4
2645	6-22-66	11-1-66	8928	9247	3.4
2610	6-6-66	11-2-66	9921	10041	1.2

TABLE III

COMPARATIVE RESULTS OF ANALOG AND DIGITAL BONE DENSITY MEASUREMENTS MADE AFTER FINAL DIGITAL PROGRAM CHANGE

SUBJECT AND X-RAY DATE		TRACING DATE	INTEGRATED COUNTS UNDER BONE SCAN Analog	Digital	PER CENT DIFFERENCE
V	8-8-66	11-3-66	11896	11824	-0.60
X	7-17-66	11-4-66	11301	11230	-0.63
X	7-18-66	11-5-66	10602	10510	-0.87
X	7-19-66	11-7-66	10724	10701	-0.21
X	7-20-66	11-8-66	11409	11360	-0.43
S	8-11-66	11-9-66	9244	9170	-0.80
W	9-2-66	11-10-66	10731	10828	+0.91
W	9-3-66	11-11-66	10875	10938	+0.58
V	8-11-66	11-12-66	11538	11476	-0.54
S	8-12-66	11-14-66	8962	8911	-0.57
S	8-13-66	11-15-66	8943	8969	+0.29
S	8-14-66	11-16-66	9486	9540	+0.57
S	8-15-66	11-17-66	8994	8961	-0.37
S	8-17-66	11-18-66	8761	8820	+0.67
S	8-18-66	11-19-66	8811	8769	-0.48
S	8-19-66	11-21-66	8908	8988	+0.90
S	8-20-66	11-22-66	9064	8993	-0.78
S	8-21-66	11-23-66	9092	9158	+0.73
S	8-22-66	11-24-66	8994	9026	+0.36
S	8-23-66	11-28-66	8951	9026	+0.84
S	8-25-66	11-29-66	8817	8865	+0.54
S	8-26-66	11-30-66	8812	8901	+1.00
S	8-27-66	12-1-66	9061	9004	-0.63
S	8-28-66	12-2-66	8804	8773	-0.35
S	8-29-66	12-3-66	9244	9201	-0.47
S	8-30-66	12-5-66	8811	8724	-0.99
P	8-30-66	12-6-66	10293	10216	-0.75
P	6-16-66	2-6-67	10139	10232	+0.92
P	6-14-66	2-6-67	9979	10064	+0.85

TABLE III (continued)

SUBJECT AND X-RAY DATE	TRACING DATE	INTEGRATED COUNTS UNDER BONE SCAN Analog	Digital	PER CENT DIFFERENCE
P 6-18-66	2-6-67	10363	10406	+0.41
P 6-20-66	2-6-67	10291	10356	+0.63
P 6-22-66	2-6-67	9983	10039	+0.56
P 6-23-66	2-6-67	10307	10411	+1.01
P 6-24-66	2-6-67	10218	10298	+0.78
P 6-25-66	2-7-67	10096	10132	+0.36
P 6-27-66	2-7-67	9992	10064	+0.72
P 6-28-66	2-7-67	10296	10349	+0.51
P 6-29-66	2-7-67	10221	10298	+0.75
P 6-30-66	2-7-67	10314	10418	+1.01
P 7-1-66	2-7-67	10139	10212	+0.72
P 7-2-66	2-7-67	10249	10250	+0.01
P 7-3-66	2-7-67	10308	10361	+0.51
P 7-4-66	2-8-67	10304	10297	-0.07
P 7-5-66	2-8-67	10614	10649	+0.33
P 7-6-66	2-8-67	10384	10428	+0.42
P 7-7-66	2-8-67	10320	10375	+0.53
P 7-8-66	2-8-67	10320	10397	+0.75

The distribution of the 57 data points obtained after the program change was also checked. The histogram showed a peak on each side of the mean instead of the expected single peak about the mean. Statistically, the hypothesis that the samples came from a normal distribution could be rejected at the 99.5% confidence level. Analysis was continued with the assumption of a gaussian distribution because

1) the data from the previous run appeared gaussian, and
2) there is no reason to expect the data to be distributed in a manner other than gaussian.

Based on the 57 data points obtained after the program change, the sample mean error was 0.11% with a sample standard deviation of 0.64%. Tolerance interval estimates obtained from the data indicate that the probability is 99% that at least 99% of all readings from the digital system will agree within -2.05% to +2.27% of the readings from the analog system.

B. System Maintenance

The system maintenance procedures were given in the Phase I Report.[7] Kaman Instruments kept the digital computer under a manufacturers service contract for the duration of Contract NAS 9-5880. The cost of a service contract is $231 per month.

[7] "Development of Instrumentation for Measurement of Bone Density", Phase I Report, Contract NAS 9-5880, January 10, 1967.

During the period of the service contract, the following service calls were made:

August 25, 1966	Accumulator Problems
September 14, 1966	A/D Problem - Teletype Logic
October 11, 1966	Tape and Operator Problems

The above service contract includes parts. Without a service contract the minimum charge for each of the above service calls is $180 plus parts.

On the basis of the above history, a service contract is more expensive than on-call service. However, the service contract includes periodic system checks which provide some degree of protection against a small error affecting the data for an extended period of time. In this particular case it is difficult to make a specific recommendation concerning service. Since no highly skilled computer operators are available at the computer, it appears that the service contract type of service affords a rather inexpensive form of insurance that the system is operating properly.